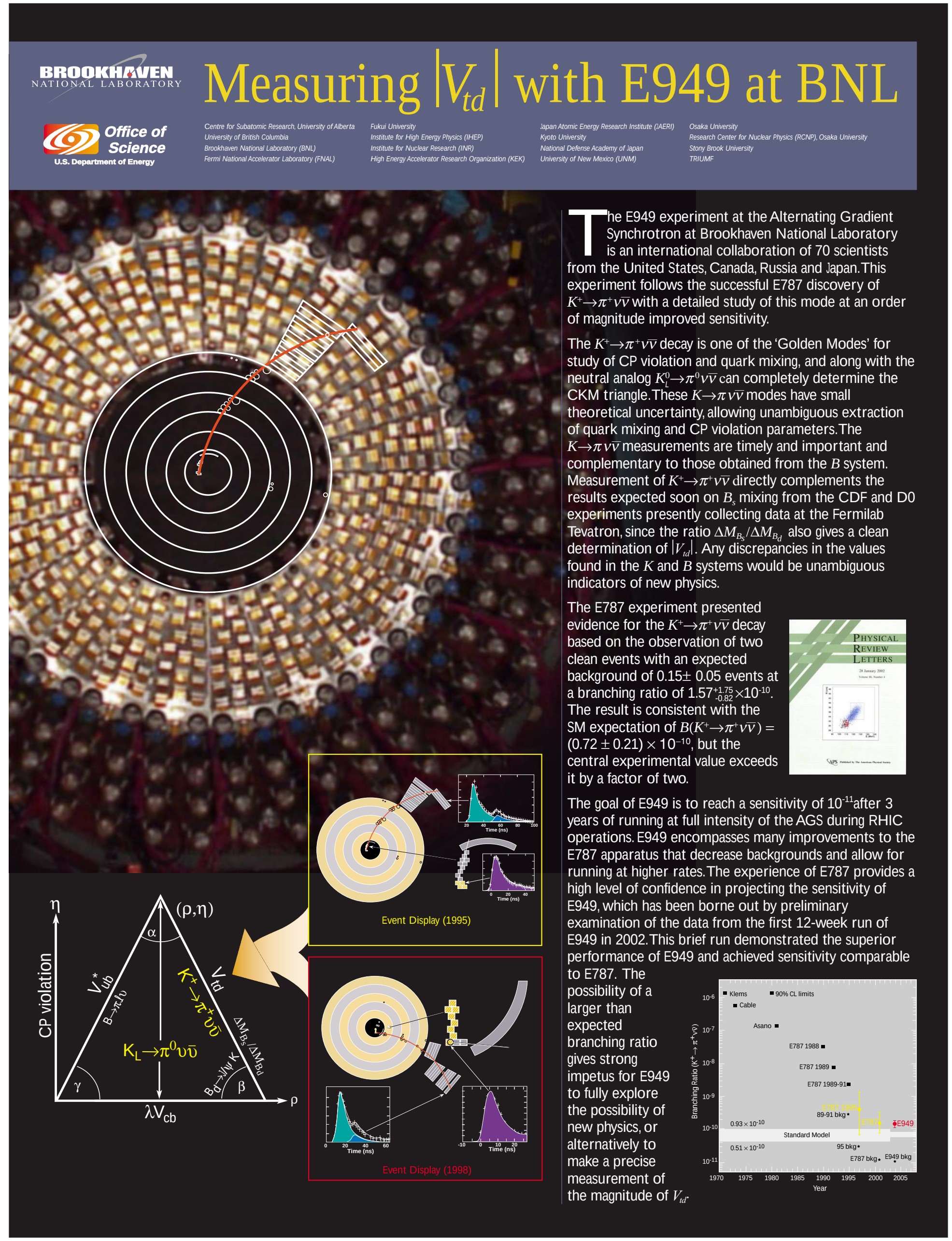
An Overview of AGS experiment E949: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

Steve Kettell

BNL

- Why is $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ interesting?
- How to do the experiment.
- Some aspects of the detector
- Some aspects of the analysis
- Conclusions

STAR Meeting, BNL, July 12, 2004



E949

An experiment to measure the branching ratio $B(K^+ \to \pi^+ \nu\bar{\nu})$

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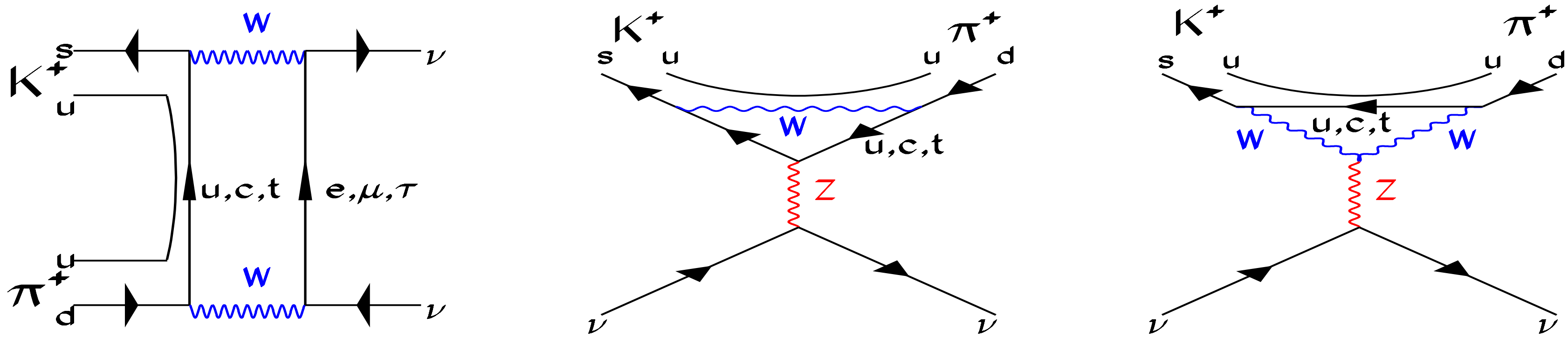
TRIUMF

Students and post-docs in red.

$\sim$70 physicists, plus a lot of hard work from earlier E787 collaborators.

How does $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ occur?

$\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$, a FCNC, is forbidden at 1^{st} order and suppressed at 2^{nd} order; since $m_t >> m_c, m_u$ $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ proceeds at a small rate and with strong sensitivity to $|V_{td}|$.



The intrinsic uncertainty in calculating $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\overline{\nu})$ from the fundamental CKM parameters is small (and may get smaller):

- hadronic matrix element is extracted from $K^+ \rightarrow \pi^0 e^+ \nu$ (isospin and p.s. corrections)
- NLO QCD calculation has significantly reduced the uncertainty, dominated by c-quark
- long distance effects are negligible
- 2-loop electroweak calculations completed (correction $\mathcal{O}(1\%)$)
- total intrinsic theoretical uncertainty is $\sim$5%

$$\begin{aligned}
\mathcal{B}(K^+ \rightarrow \pi^+ \nu\overline{\nu}) &= \frac{\kappa_+ \alpha^2 B(K^+ \rightarrow \pi^\circ e^+ \nu_e)}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t\lambda_t + X_c\lambda_c|^2 \\
&= (0.8 \pm 0.1) \times 10^{-10}
\end{aligned}$$

where $|\lambda_i| \equiv |V_{is}^* V_{id}|, i = u, c, t$. The $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\overline{\nu})$ uncertainty is currently limited by our imperfect knowledge of $|V_{td}|$. $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ provides a clean determination of $|V_{td}|$.

Unitarity Triangle and Quark Mixing

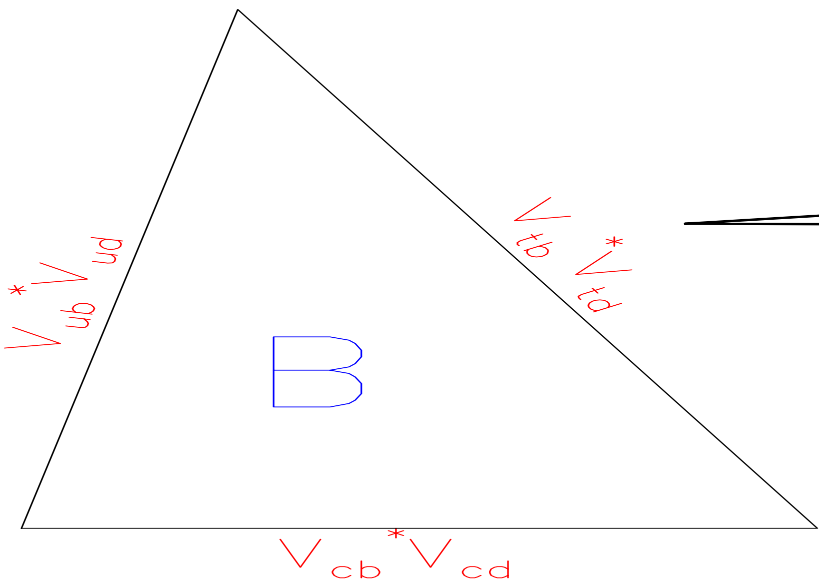
In the SM the CKM matrix relates flavor and weak eigenstates. and with 3 generations naturally explains CP violation through the phase $\bar{\eta}$:

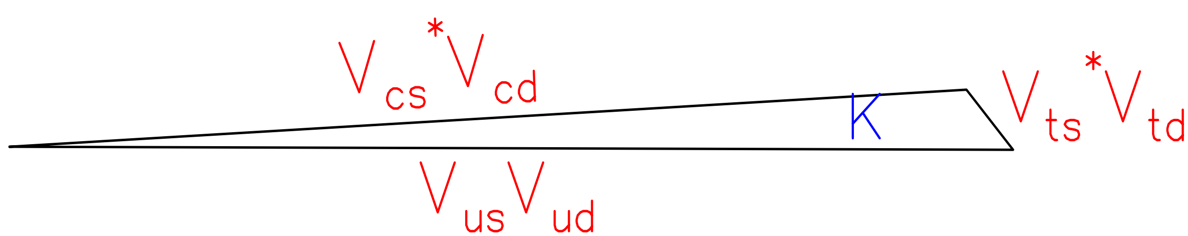
$$\begin{pmatrix} \mathrm{V_{ud}} & \mathrm{V_{us}} & \mathrm{V_{ub}} \\ \mathrm{V_{cd}} & \mathrm{V_{cs}} & \mathrm{V_{cb}} \\ \mathrm{V_{td}} & \mathrm{V_{ts}} & \mathrm{V_{tb}} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

This gives 6 relations equal to 0. For example:

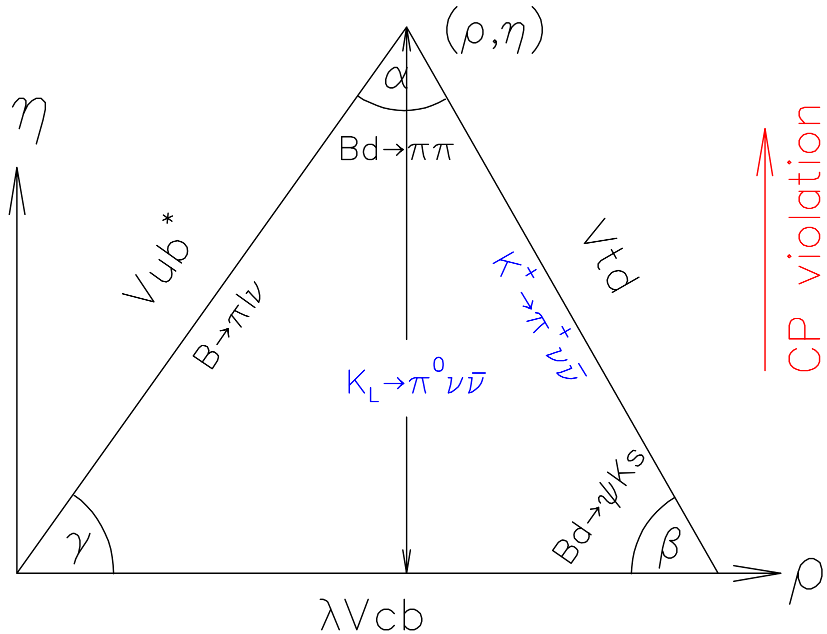
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{or} \quad \lambda_u + \lambda_c + \lambda_t = 0$$

can be drawn in the complex plane as a triangle (Unitarity triangle):





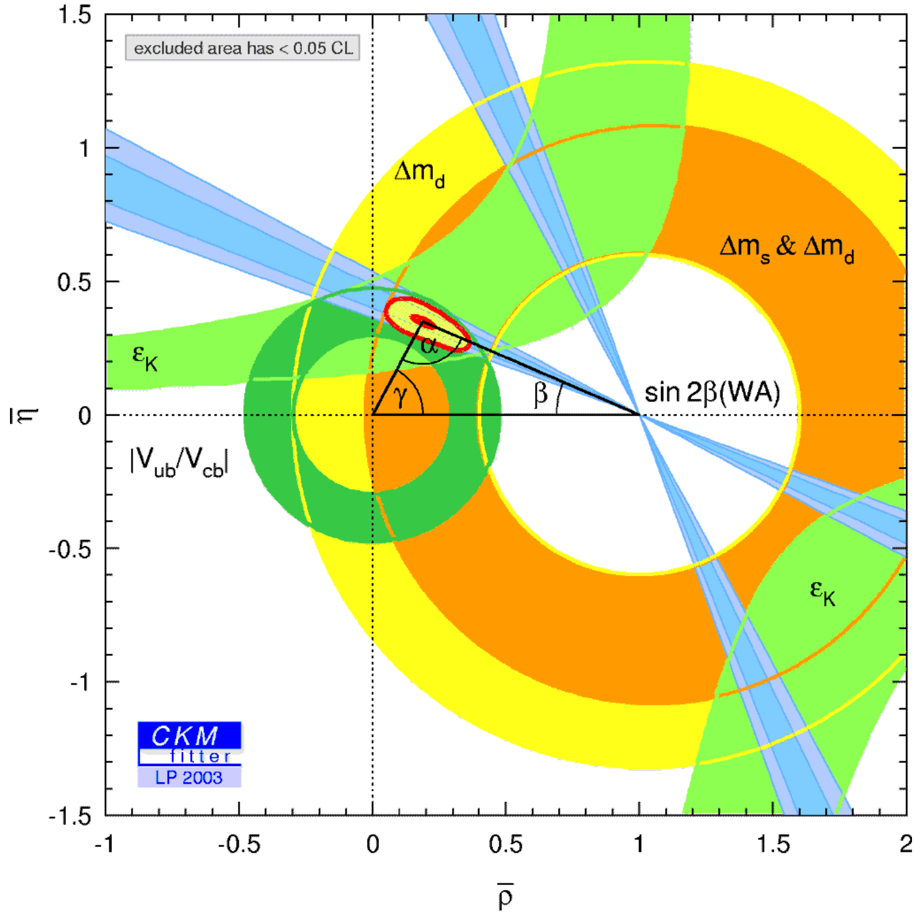
Processes with small theoretical uncertainties



Process	Experiments
$\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S})$	BaBar, Belle
CP violating decay rate asymmetry	
$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV
ratio of mixing frequencies of B_s and B_d mesons	

- Comparison of $|V_{td}|$ from $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and from $\Delta M_{B_s}/\Delta M_{B_d}$ provides an important test of the SM.
- Comparison of $\sin 2\beta$ from $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \to \pi^0\nu\bar{\nu})/\ \mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ and from $\mathcal{A}(B \to J/\psi \mathrm{K}^0_\mathrm{S})$ is perhaps **the** definitive test of the SM picture of CP violation.

Current CKM picture



The measurement of sin2β is getting better; a better measurement of $|V_{td}|$ is called for.

We have two modes with small theoretical ambiguity: $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+ \nu\overline{\nu}$.

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 0.4 \times 10^{-10} \times \left(P_{charm} + \frac{A^2 X(x_t)\xi}{\lambda}\sqrt{\frac{\Delta M_{B_d}}{\Delta M_{B_s}}}\right)^2 < 1.4 \times 10^{-10}$$

- Current limit on $\Delta M_{B_s} > 14.4 ps^{-1}$ (95% CL) (HFAG 2004)
- Current best estimate of $\xi = 1.15 \pm 0.05^{+0.12}_{-0.00}$ (CKM-LWG)
- $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$(E787, PRL **88**, 041803 (2002))

E949 Status

History:

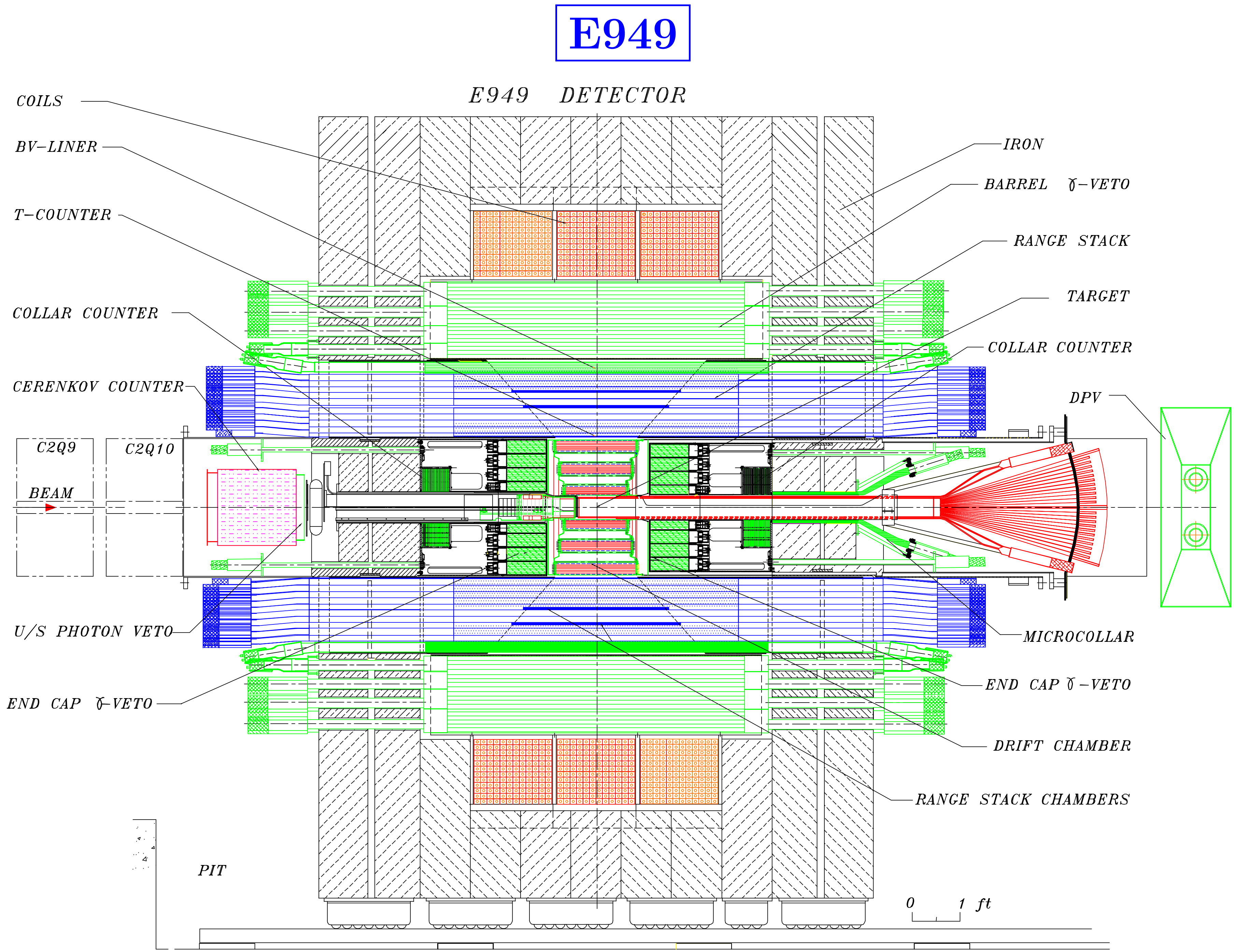
- October 1998: E949 endorsed by BNL HENP PAC as 'must do'
- August 1999: E949 approved by DOE-HEP to run for 60 weeks
- Fall 2001: E949 engineering run with RHIC-HI
- Spring 2002: E949 data run (12 weeks)

Proposal:

beam: LESB3, low energy (600-800 MeV/c) separated K^+ beam. The beam conditions are expected to be a 730 MeV/c K^+ beam with a K/π ratio of >3:1 with 65 Tp on the C-target. The expected spill length is ~4.1 sec and a Duty Factor of 64%.

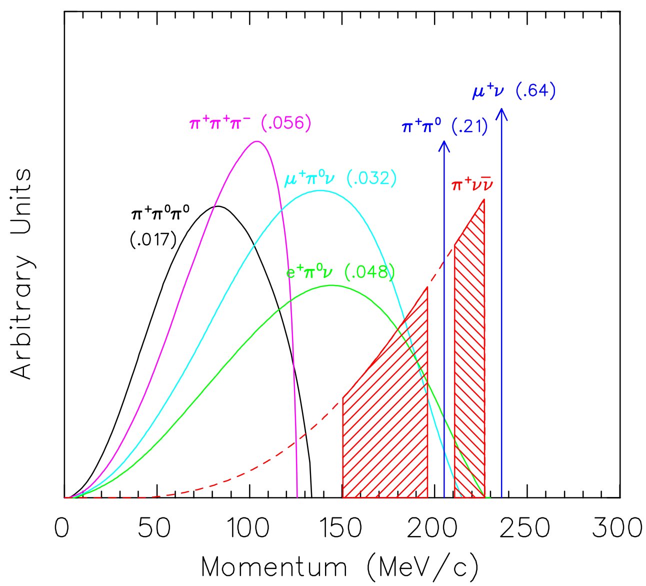
detector: Solenoidal magnetic spectrometer, with 4π calorimetric detection of all decay products except neutrinos.

hours: Request 6,000 hours. This should represent 2 years of running in the RHIC era. Expect to be ready for data collection during the fall of 2000.


E949
E949 DETECTOR
COILS
BV–LINER
T–COUNTER
COLLAR COUNTER
CERENKOV COUNTER
C2Q9
C2Q10
BEAM
U/S PHOTON VETO
END CAP γ–VETO
PIT
IRON
BARREL γ–VETO
RANGE STACK
TARGET
COLLAR COUNTER
DPV
MICROCOLLAR
END CAP γ –VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
0 1 ft

Experimental Considerations for $K^+ \to \pi^+\nu\overline{\nu}$

- 3-body decay with 2 missing particles $\Rightarrow 0 \leq P_{\pi+} \leq 227\mathrm{MeV}/c$ ...and $\mathcal{B} < 10^{-10}$
- Must veto extra particles to $\leq 10^{-3}$
- Particle identification (PID) is essential.
- Redundant precise kinematic measurements.
- Supress backgrounds by 10^{11}



$P_{\pi+}$ in K$^+$ rest frame

Process	$\mathcal{B}$	PID	veto	kin.	time
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	0.21	-	√ √	√	-
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	0.63	√	-	√	-
$K^+ \to \mu^+\nu\gamma$	0.005	√	√	-	-
$K^+ \to \pi^0\mu^+\nu$	0.032	√	√ √	-	-
$K^+ \to \pi^0 e^+\nu$	0.048	√	√ √	-	-
$K^+ \to \pi^+\pi^-\pi^+$	0.056	-	√	√ √	-
π^+ scatter	-	√	-	-	√
$K^+ n \to K_L\ p$;					
$K_L \to \pi^+\ell^-\nu$	-	-	√	-	√

"kin." = kinematic suppression

"PID" = includes π/μ and K/π discrimination

$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 0.8 \times 10^{-10}$

$K^+ \to \pi^+\nu\bar{\nu}$: Difficult, but not impossible!

Name	**"PNN2"**	**"PNN1"**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996-97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Sensitivity (S.E.S.)	6.9×10^{-10}	0.83×10^{-10}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

E787
$K^+ \to \pi^+\nu\bar{\nu}$
results

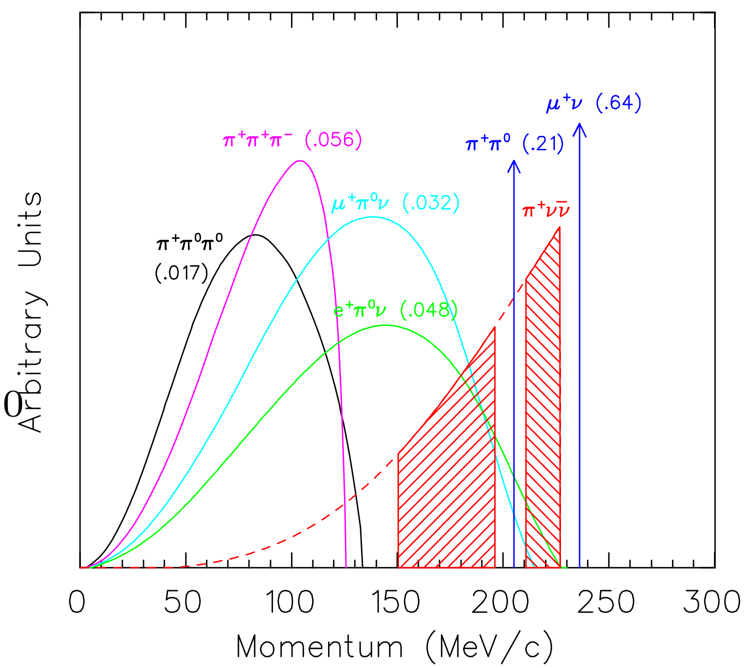
PNN1: PRL **88**, 041803 (2002).

PNN2: limit is combined from 1996 [PL **B537**, 211 (2002)] and 1997 [hep-ex/0403034] data. (1997 analysis has 27% more acceptance)

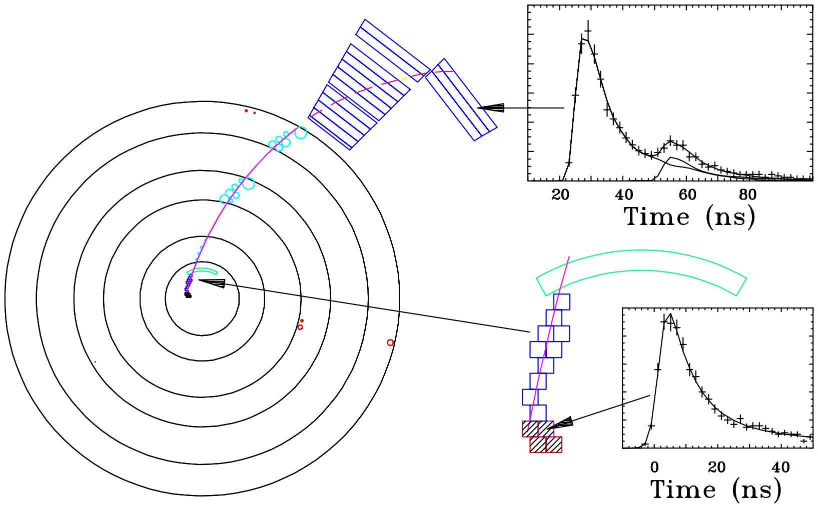
SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

Buchalla& Buras, NP**B548** 309 (1999);

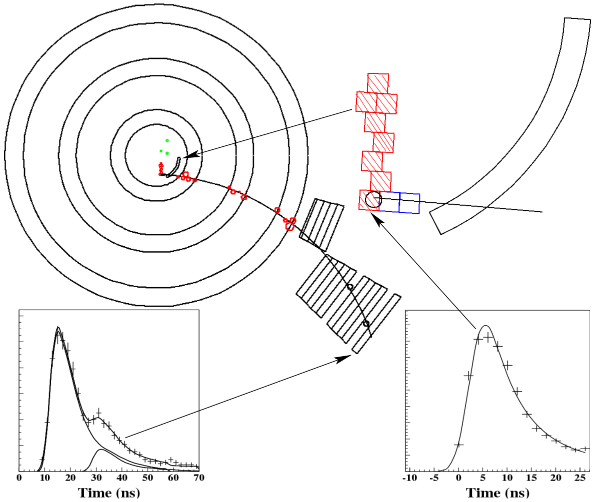
Isidori, hep-ph/0307014;Buras et al., hep-ph/0405132

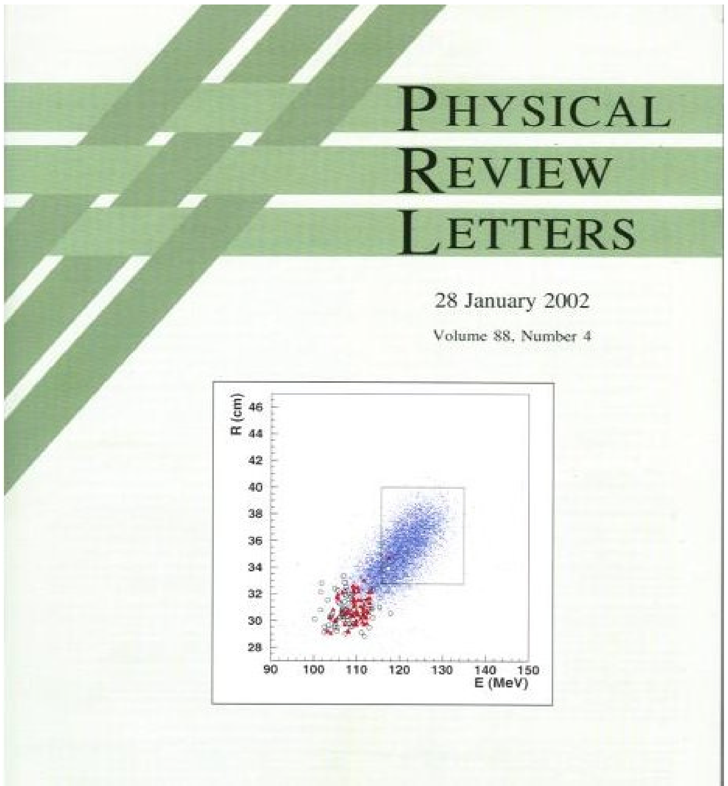


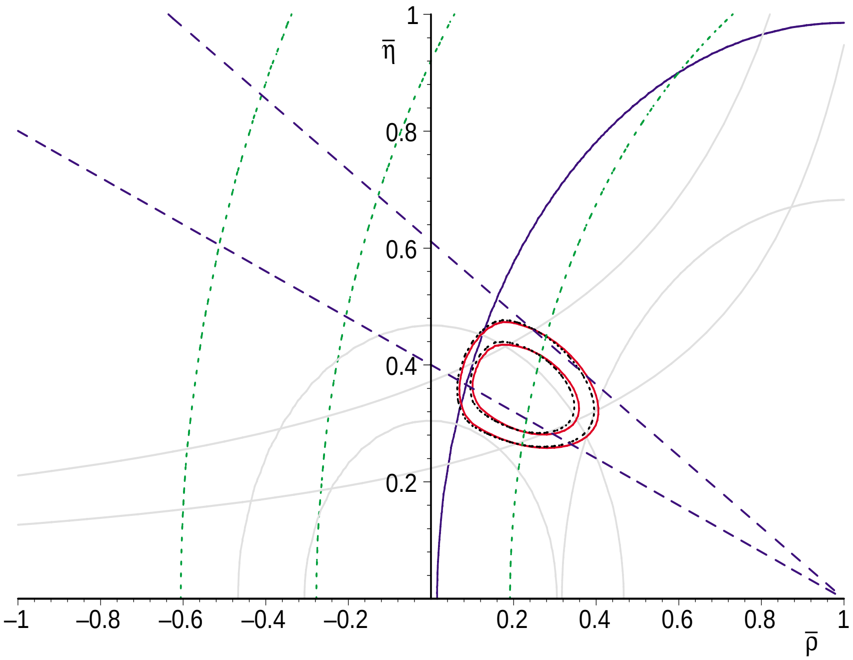
Candidate E787A



Candidate E787C

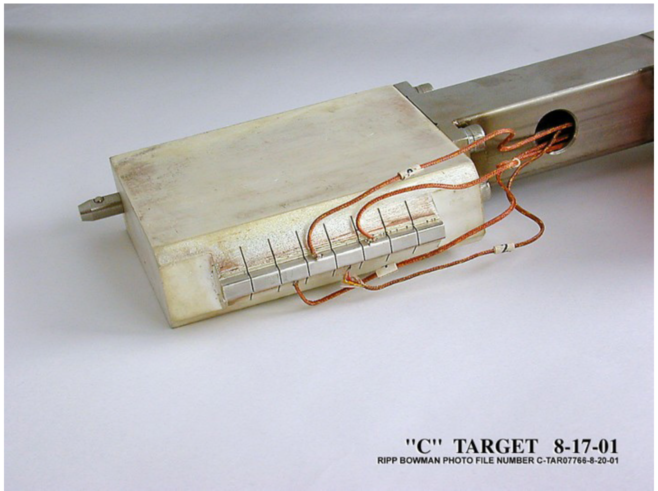




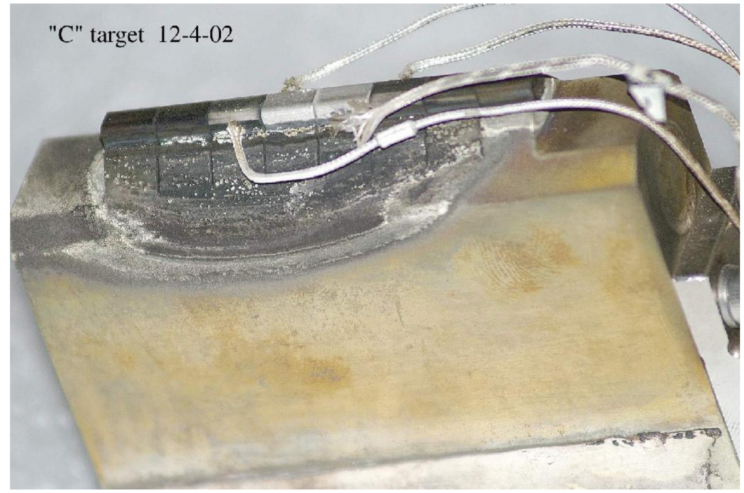


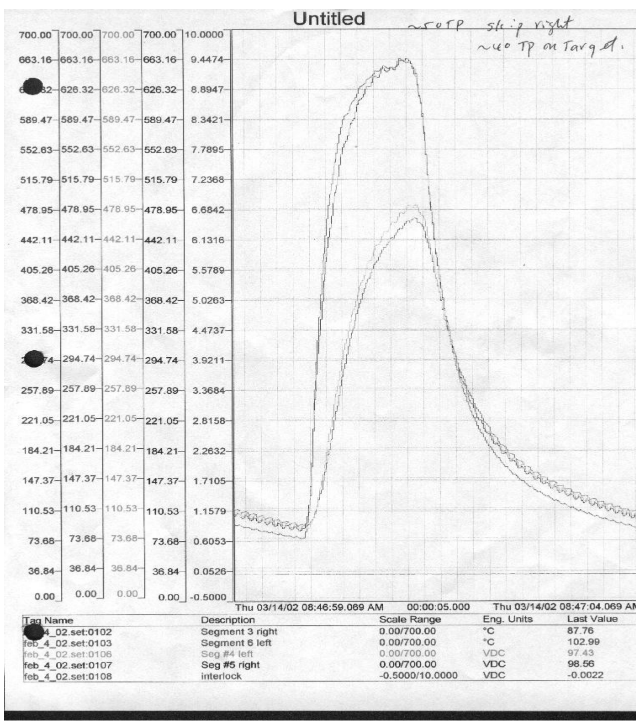
E949 production target and beamline

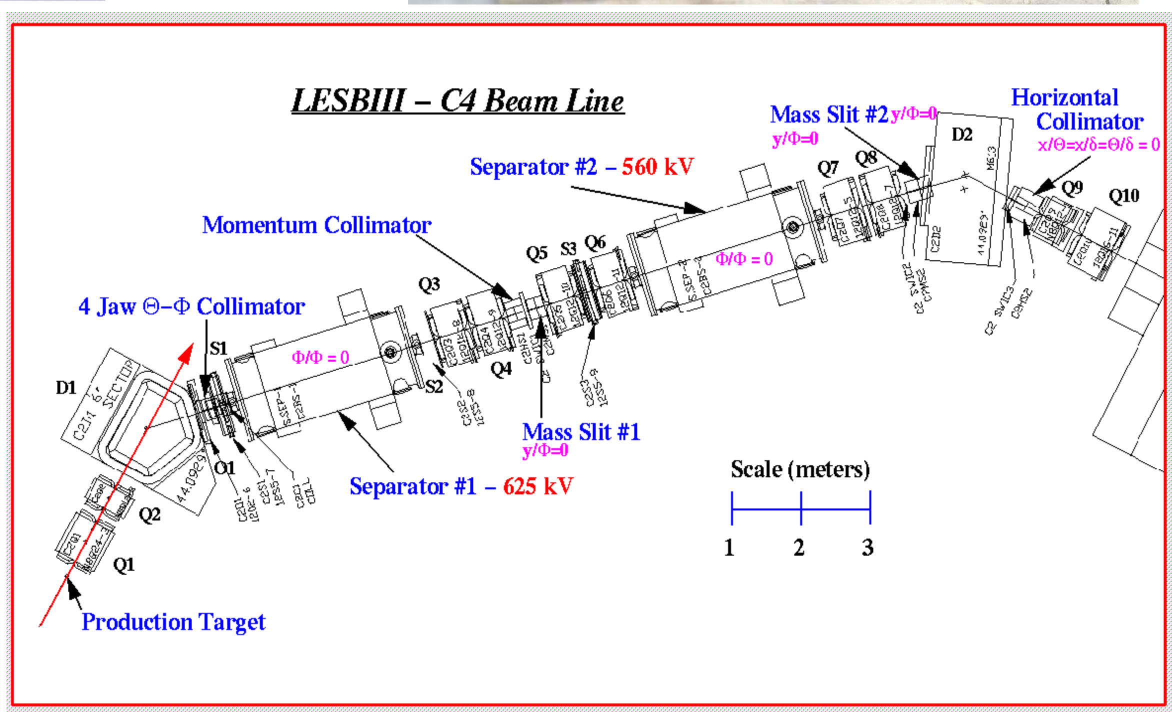
Pt Target before E949 data taking



...and after ($\sim 6 \times 10^{19}$ protons)

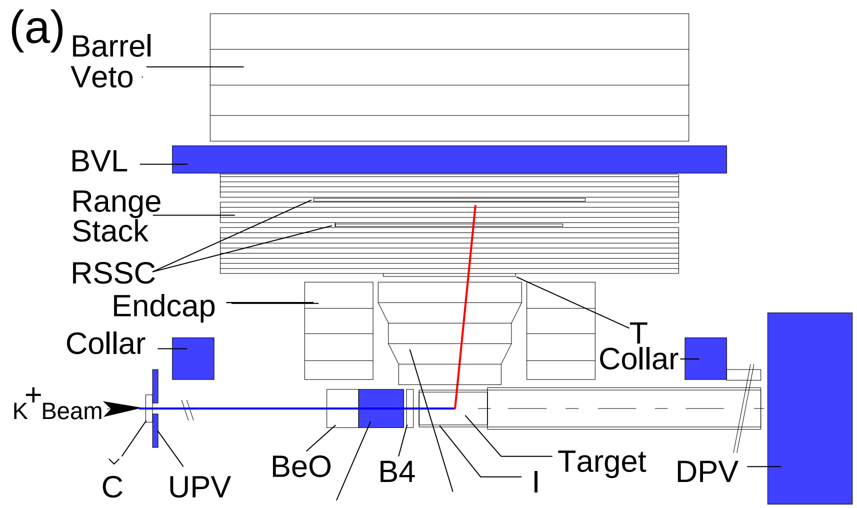


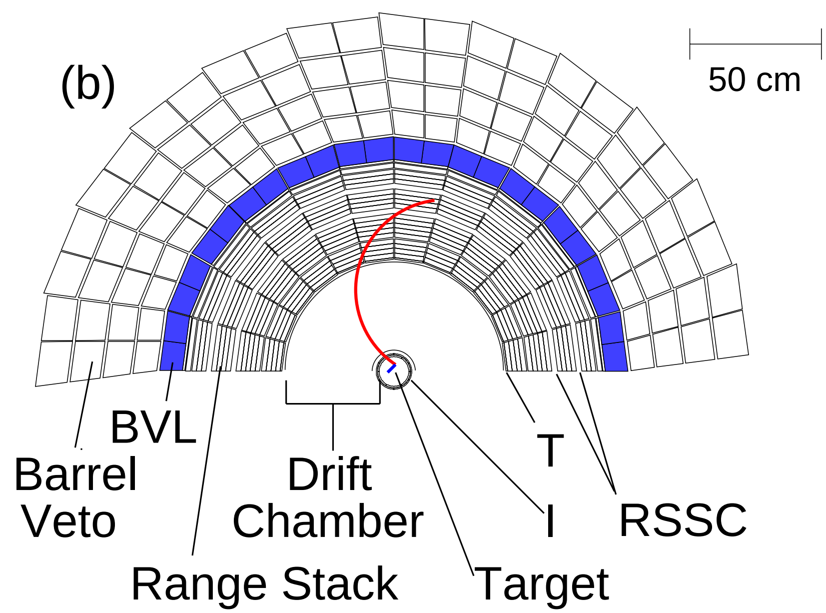


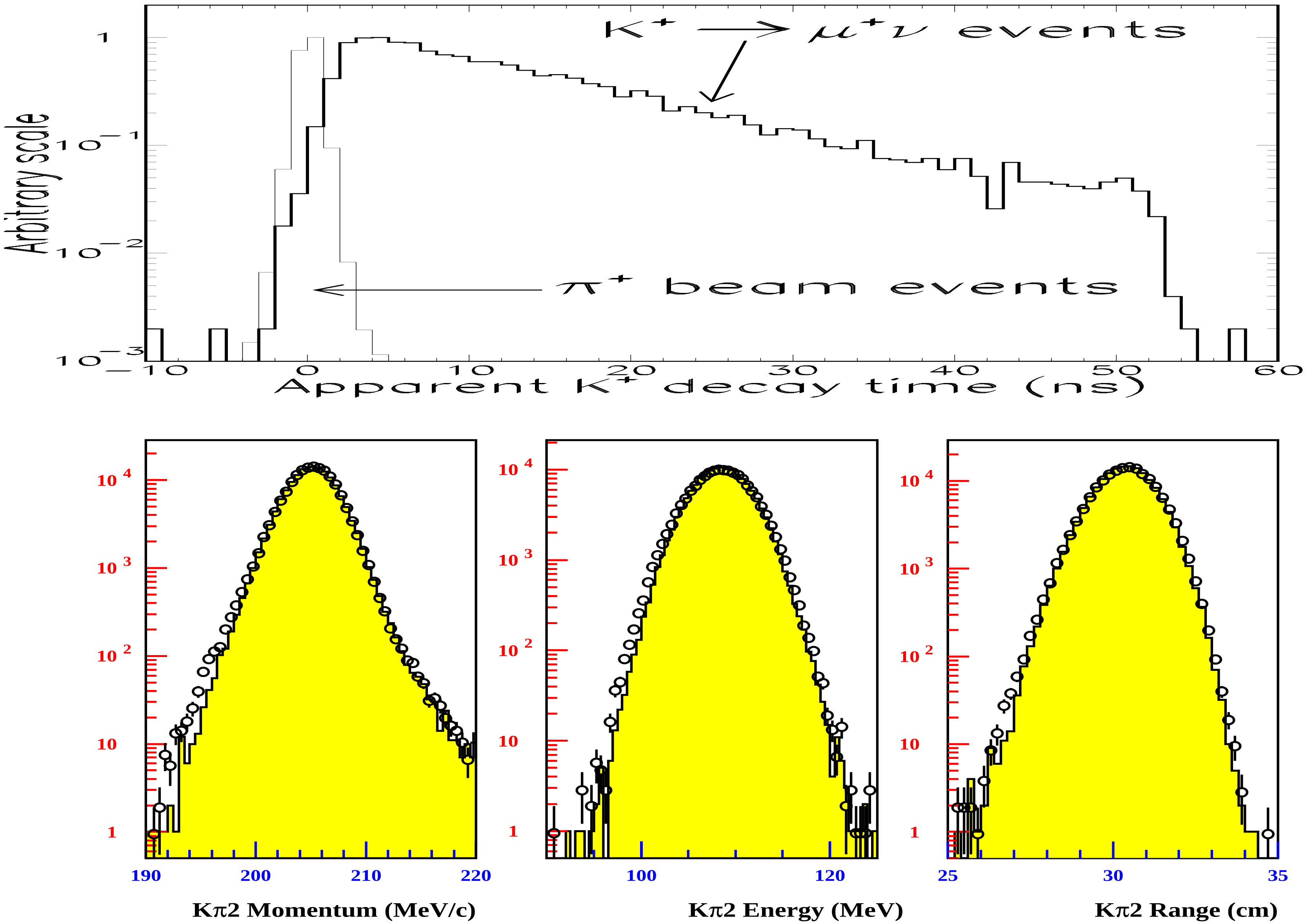


E949 method

- $\sim$ 700 MeV/c K$^+$ beam
- Stop K$^+$ in scint. fiber target
- Wait at least 2 ns for K$^+$ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**

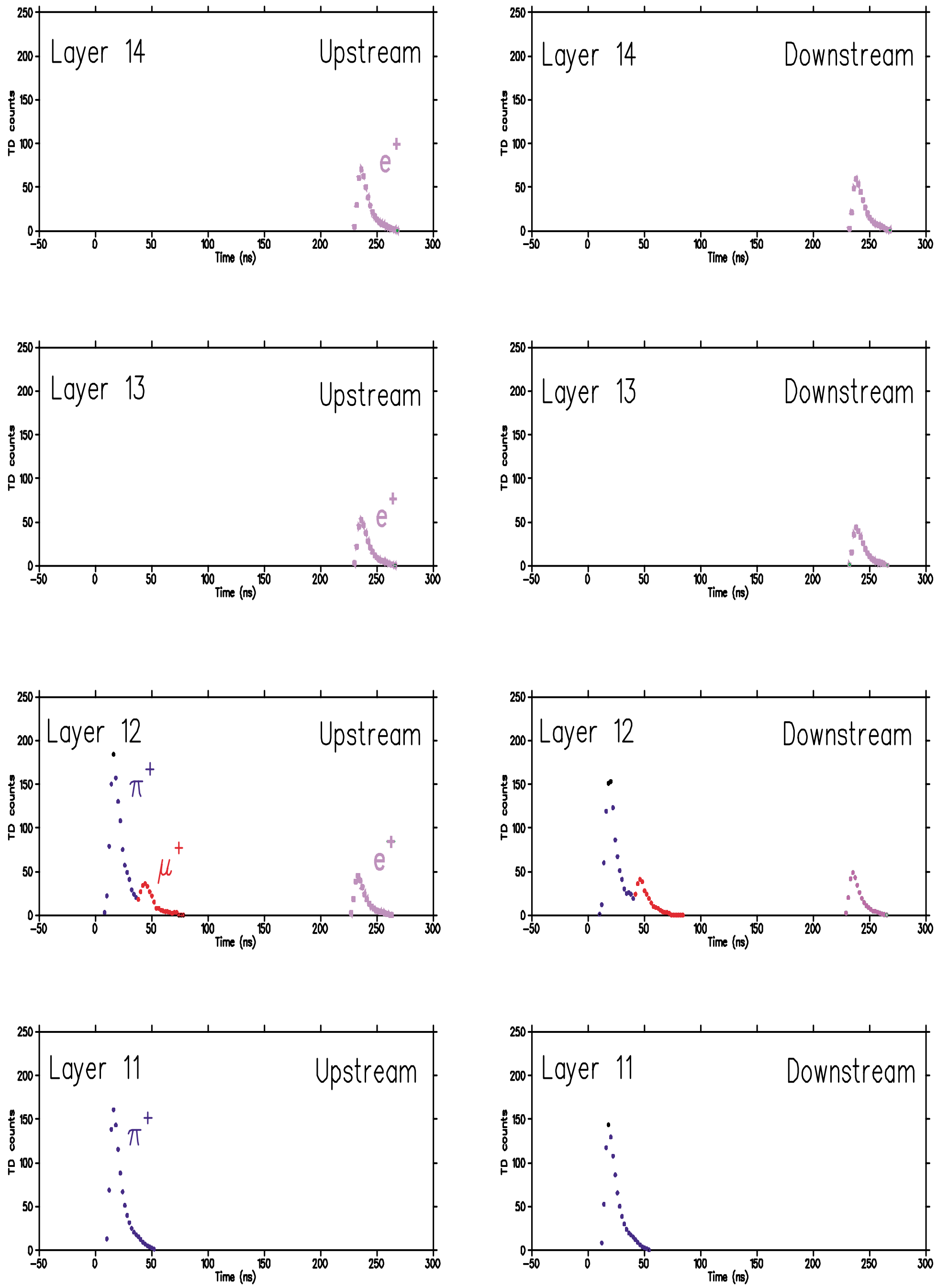






σ_P=2.3 MeV/c σ_E=3.0 MeV σ_R=0.9 cm

E787 (circles), E949 (histogram)



$\boxed{\textbf{Identify } \pi^+ \longrightarrow \mu^+ \longrightarrow e^+}$

- Sample pulse height every 2 ns for 2 μs (TDCs to 10 μs)
- π^+ stops in range stack scintillator (2 cm/layer)
- $\pi^+ \rightarrow \mu^+\nu$, $E_\mu = 4.1$ MeV, $R_\mu \sim 1$ mm, $\tau_\pi = 26.0$ ns
- $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$, $E_e \leq 53$ MeV, $\tau_\mu = 2.20$ μs

Plots: Pulse height (0 to 250) *vs* time (-50 to 300 ns)

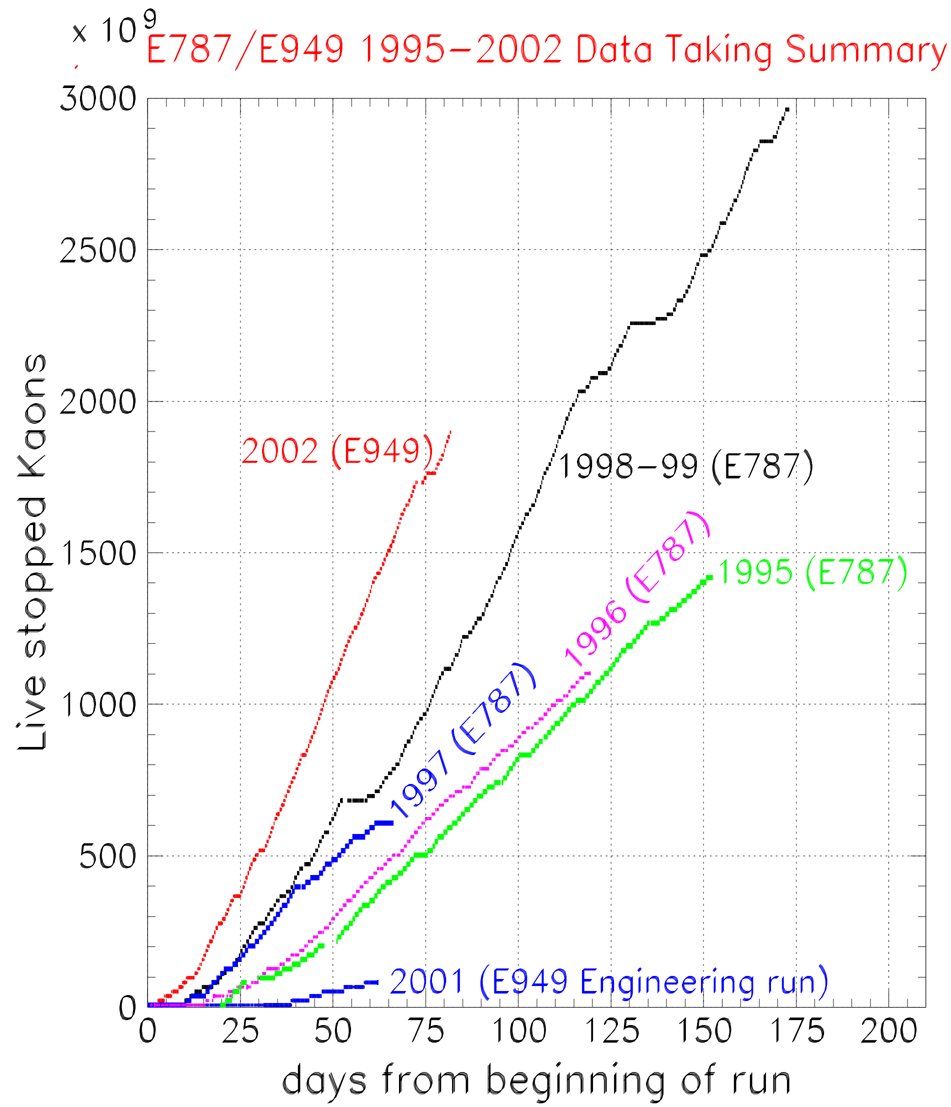
E949 compared with E787

Upgrades to E787:

- More protons from AGS
- Improved photon veto
- Improved tracking and energy resolution
- Higher rate capability due to DAQ, electronics and trigger improvements

Not optimal in 2002:

1. Duty factor.
2. Proton energy.
3. K/π separation.

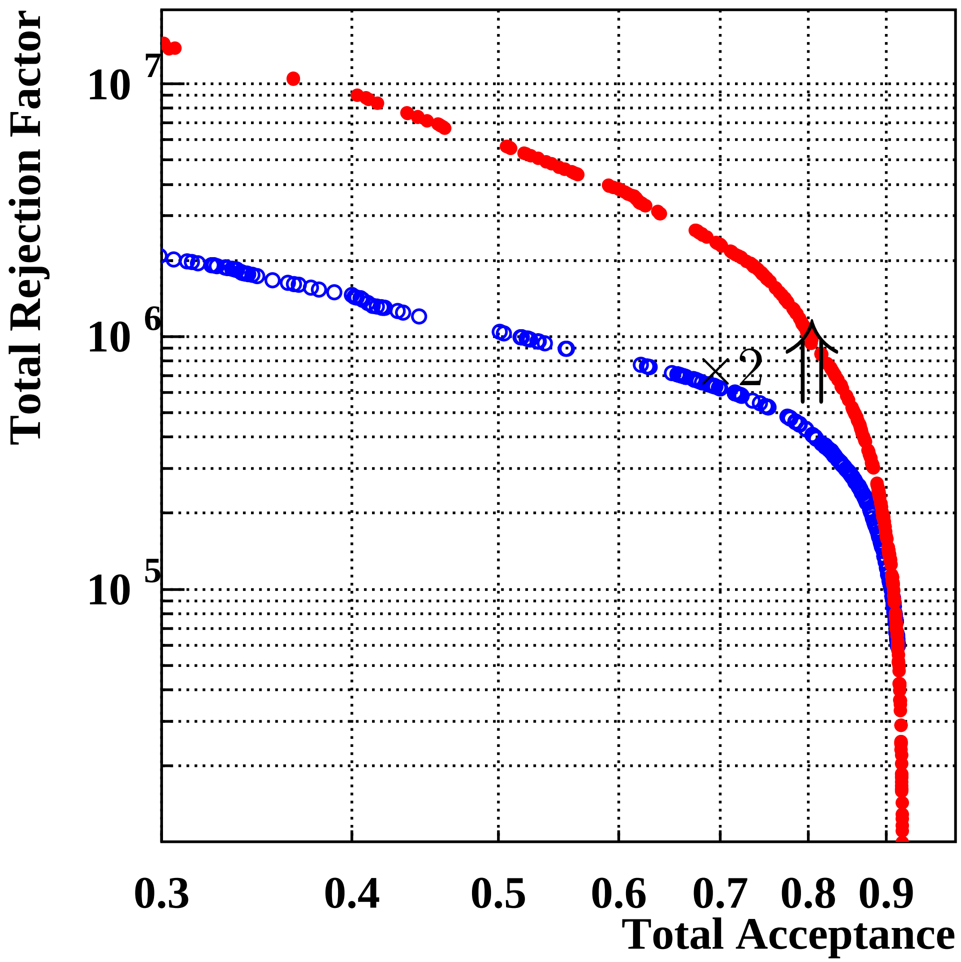


E949: Upgrade of photon veto

Improved photon veto.

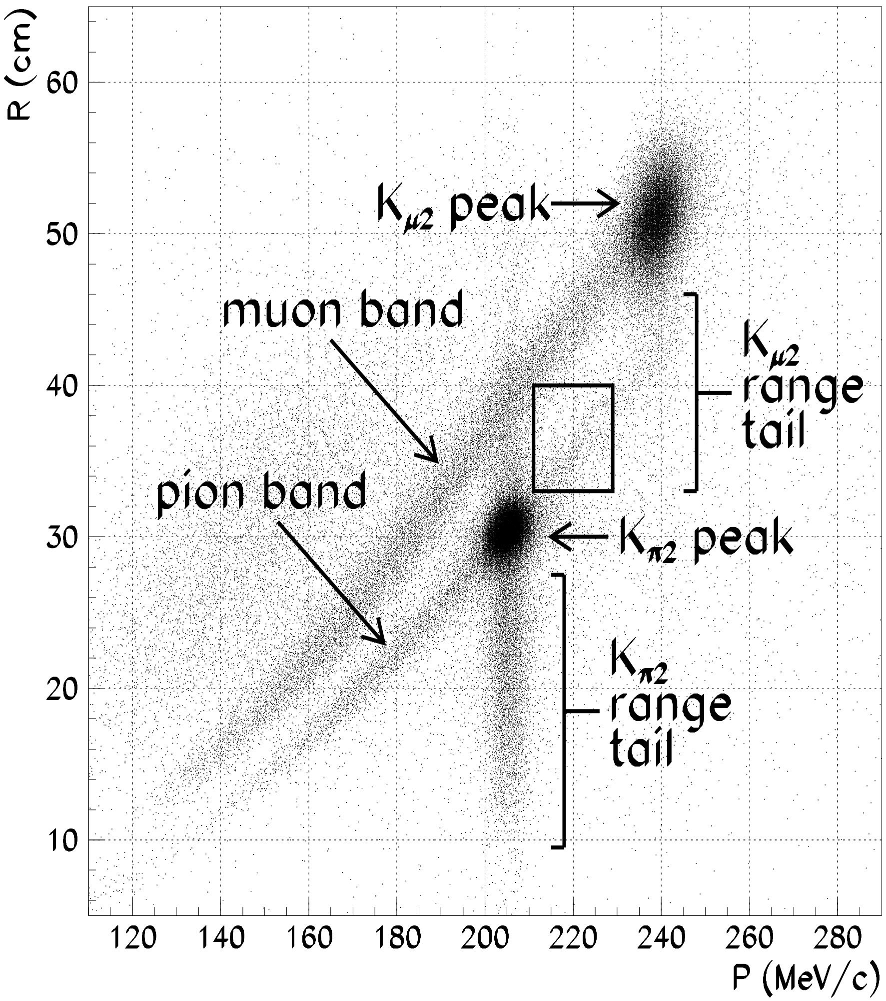
Figure: background **Rejection** as a function of $K^+ \to \pi^+ \nu \bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

$\sim$ 2$\times$ better rejection at nominal **PNN1** acceptance of 80% or $\sim$ 5% more acceptance in E949 with same rejection as E787.

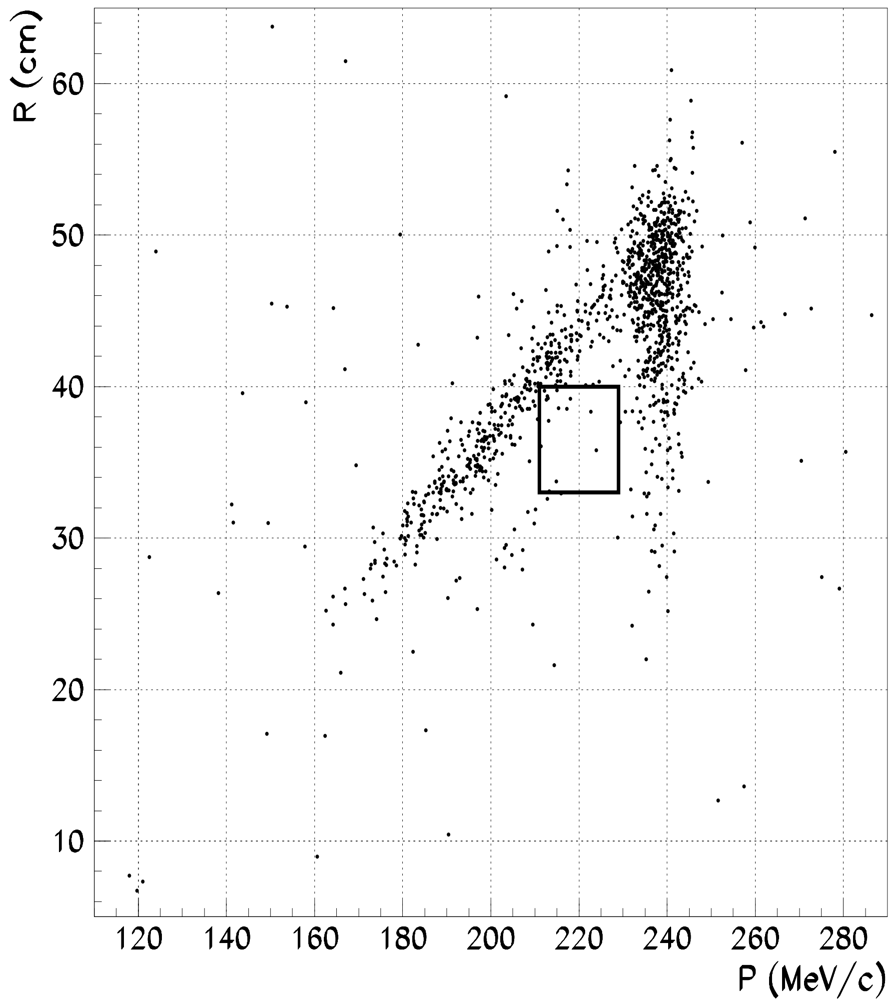


Data

Range (in cm of scintillator) vs. momentum



Minimum bias ($K_{\pi2}$) Trigger

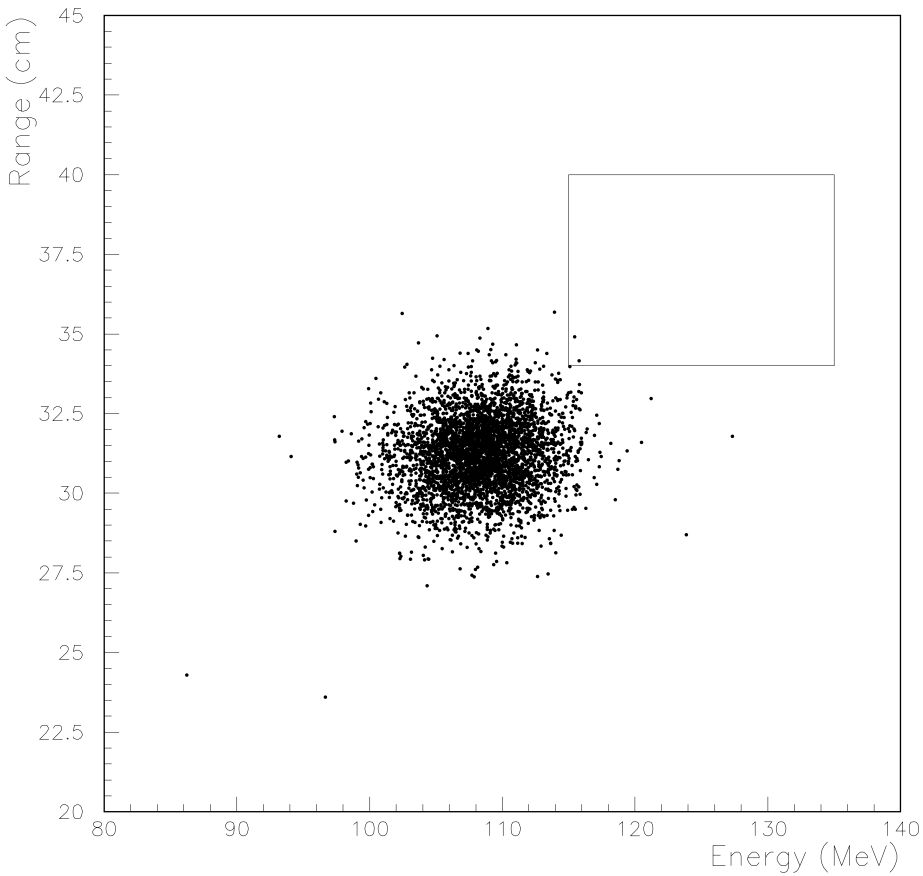


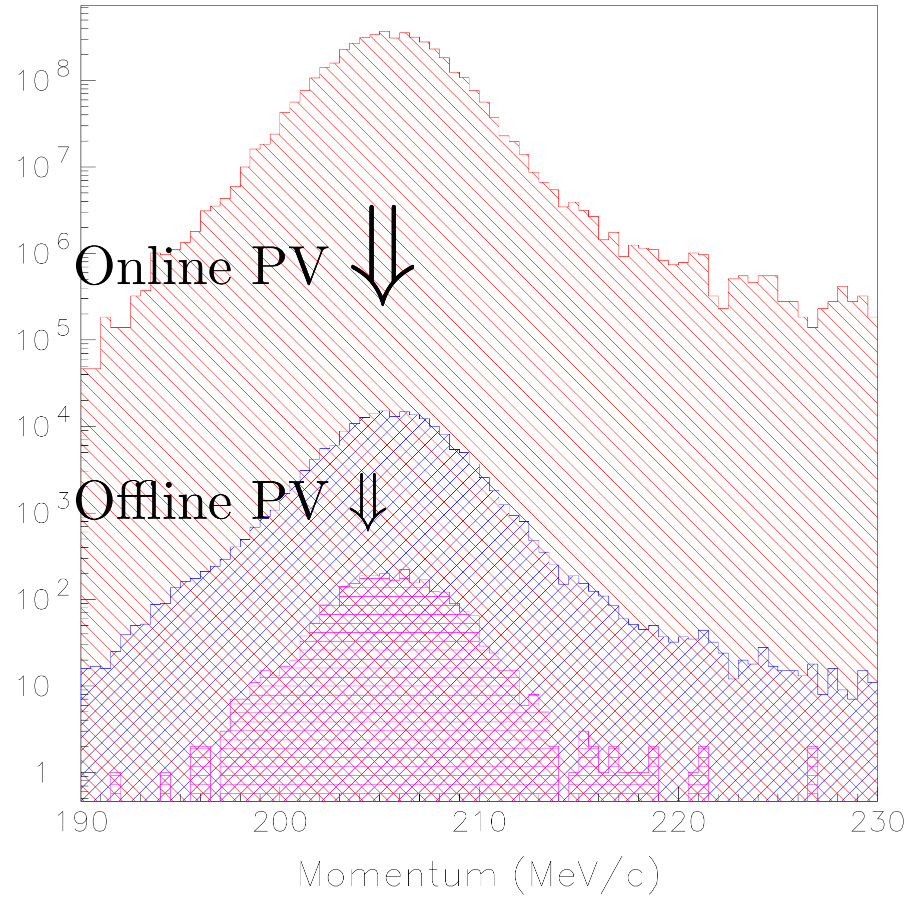
$\pi\nu\bar{\nu}$ Trigger

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(\mathrm{K}^+ \to \pi^+\pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

Example: $K^+ \to \pi^+\pi^0$ background rejection





Left: Select photons, measure rejection of kinematic cuts: P, R, E.

Right: Select $K^+ \to \pi^+\pi^0$ kinematically, measure rejection of photon veto. **Photon veto:** Typically 2–9 ns time windows and 0.2–4 MeV energy thresholds ($\bar{\epsilon}_{\pi^\circ} \leq 10^{-6}$)

Verify background prediction by loosening cuts

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

	PV$\times$KIN	10×10	20×20	20×50	50×50	50×100
$K_{\pi2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD$\times$KIN	10×10	20×20	50×50	80×50	120×50
$K_{\mu2}$	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD$\times$KIN	10×10	20×20	50×20	80×20	80×40
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\mu m} \equiv K^+ \to \mu^+\nu\gamma$, $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \pi^+\pi^0$; $\pi^+ \to \mu^+\nu$

TD$\equiv \pi \to \mu \to e$ identification, PV$\equiv$Photon Veto rej., KIN$\equiv$ kinematic rej. $M \times N \equiv$ reduction in rejection with respect to signal region ($\equiv 1\times1$)

Quantify consistency: Fit $N_{\rm obs} = cN_{\rm pred}$ and expect $c = 1$.

Background	c	χ^2 Probability	Total background
$K_{\pi2}$	$0.85^{+0.12}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu2}$	$1.15^{+0.25}_{-0.21}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40	0.024 ± 0.010

E949 improved analysis strategy

1. E787 background estimation methods are reliable
2. Divide signal region into cells and calculate background (b_i) and signal acceptance (s_i) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $K^+ \to \pi^+\pi^0$ background within "signal box"
3. Can calculate $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ using s_i/b_i of any cells containing candidates using likelihood ratio method. (see T. Junk [NIM **A434**, 435 (1999)])
4. Increase total size of signal region to increase acceptance at cost of more total background

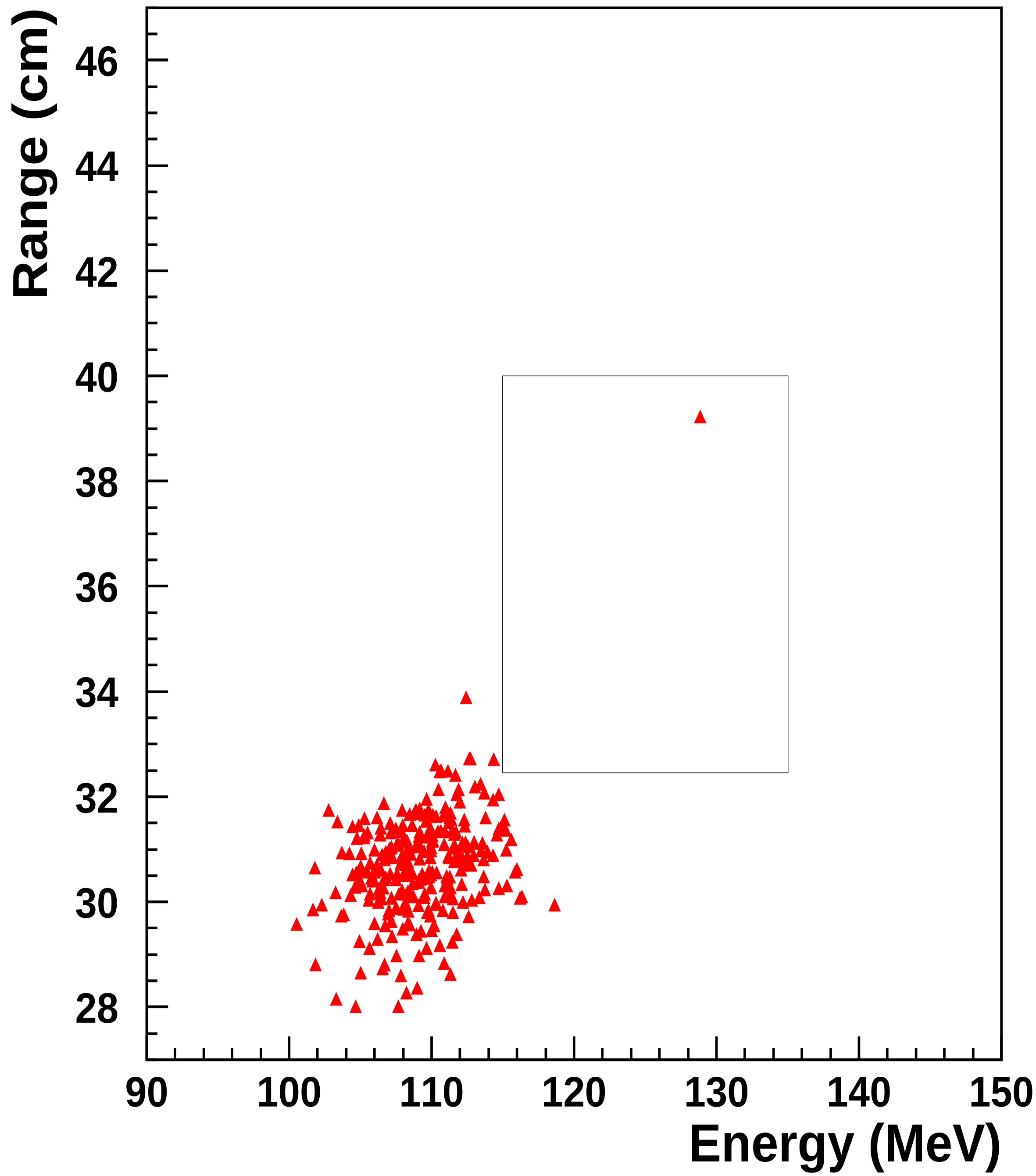
Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

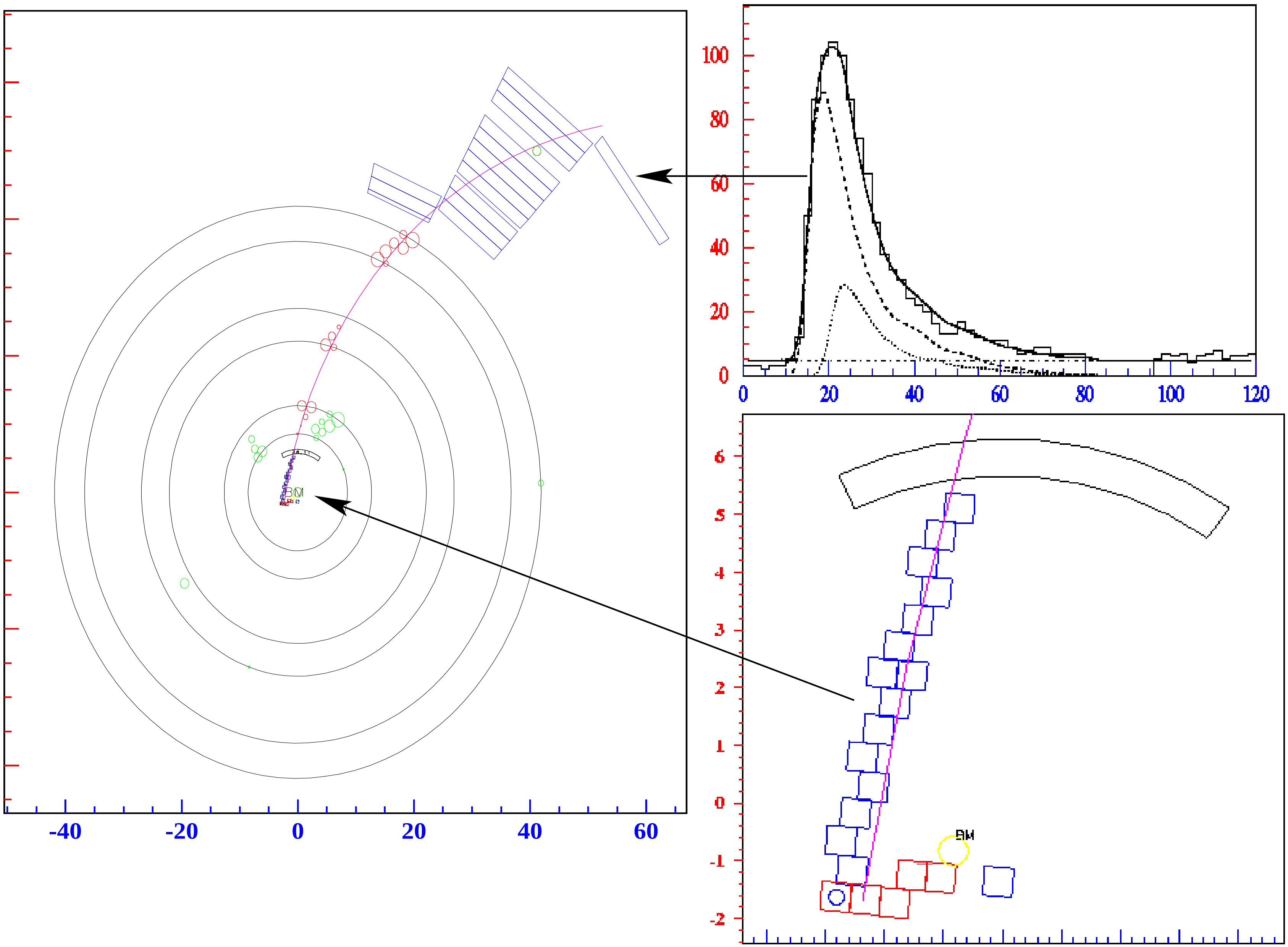
Solid line shows signal region.

Single candidate found.

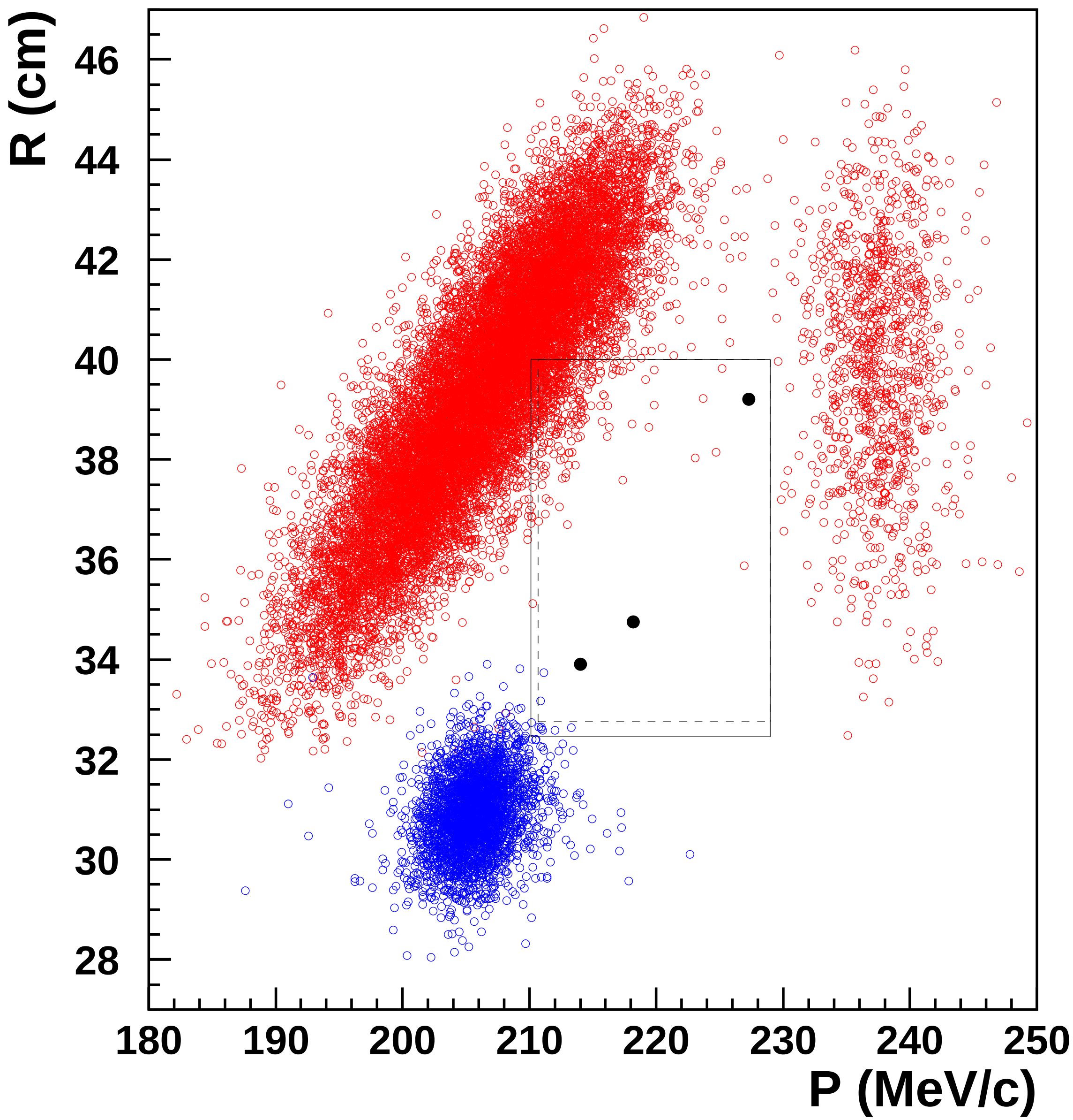
Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+\pi^0$.



Event display



What is nearby?



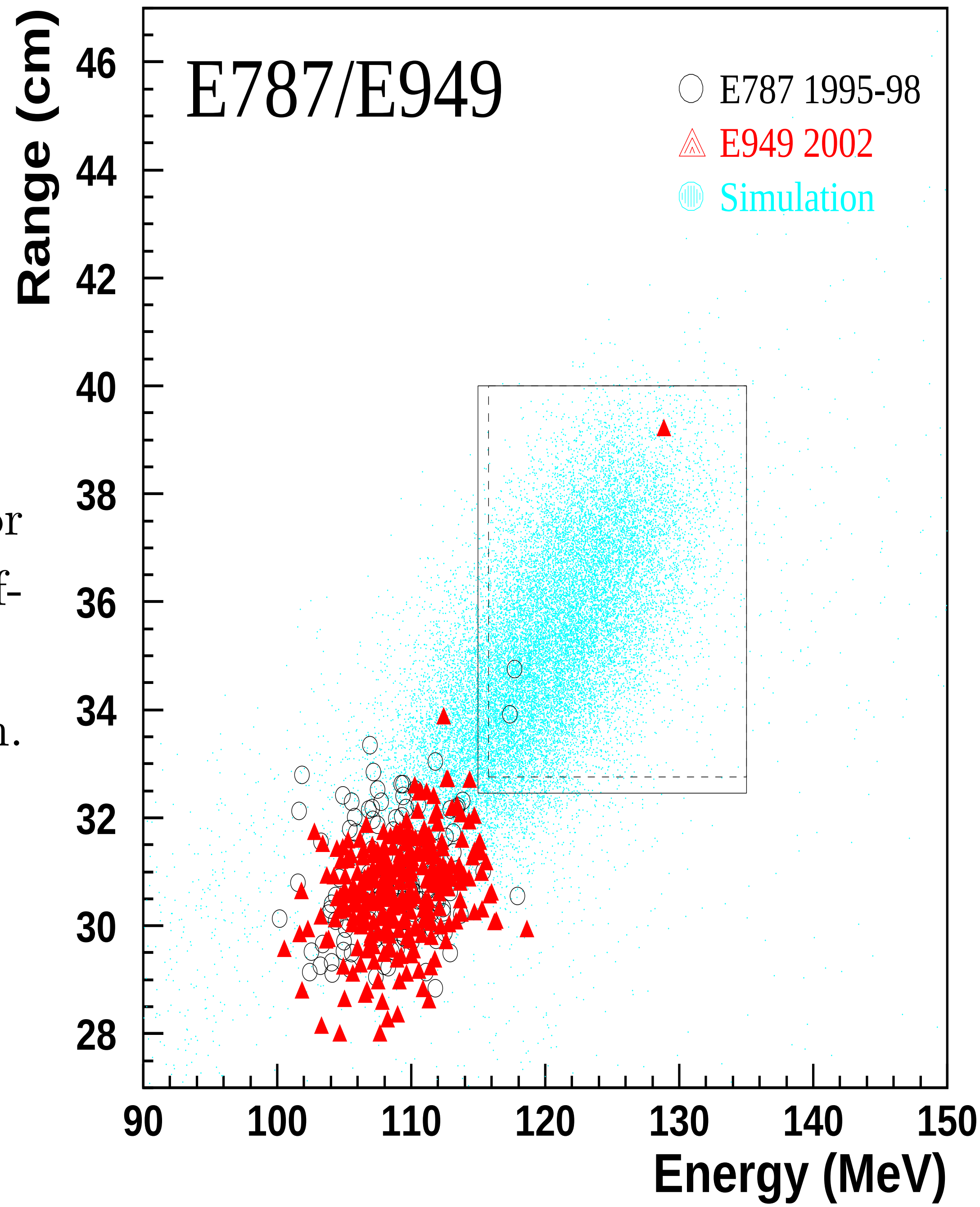
- **black points** are E787+E949 data with all cuts
- **blue points** are E949 γ-tagged data
- **red points** are E949 μ^+-tagged data (no $\pi^+ \to \mu^+$ decay)

Combined E787/E949

Range (cm) *vs.* Energy (MeV) for combined E787 and E949 data after all other cuts applied.

Dashed line is E787 signal region.

Solid line is E949 signal region.



1995–2002: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$

[see PRL **93** (2004), 31801]

	E787		E949
Stopped K$^+$ (N_K)	5.9×10^{12}		1.8×10^{12}
Total Acceptance	0.0020 ± 0.0002		0.0022 ± 0.0002
S.E.S.	0.8×10^{-10}		2.6×10^{-10}
Total Background	0.14 ± 0.05		0.30 ± 0.03
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i+b_i}$	0.98	0.88	0.48

b_i = background of cell containing candidate

$S_i \equiv \mathcal{B}A_i N_K$ = signal for cell containing candidate

$A_i \equiv$ acceptance

$\mathcal{B}$ = measured central value of $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction

$W_i \equiv S_i/(S_i + b_i)$ = *a posteriori* event weight

Combined E787 and E949 results for $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu})$

$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ (68% CL interval)

$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \overline{\nu}) > 0.42 \times 10^{-10}$ at 90% CL.

$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \overline{\nu}) < 3.22 \times 10^{-10}$ at 90% CL.

SM prediction†: $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$

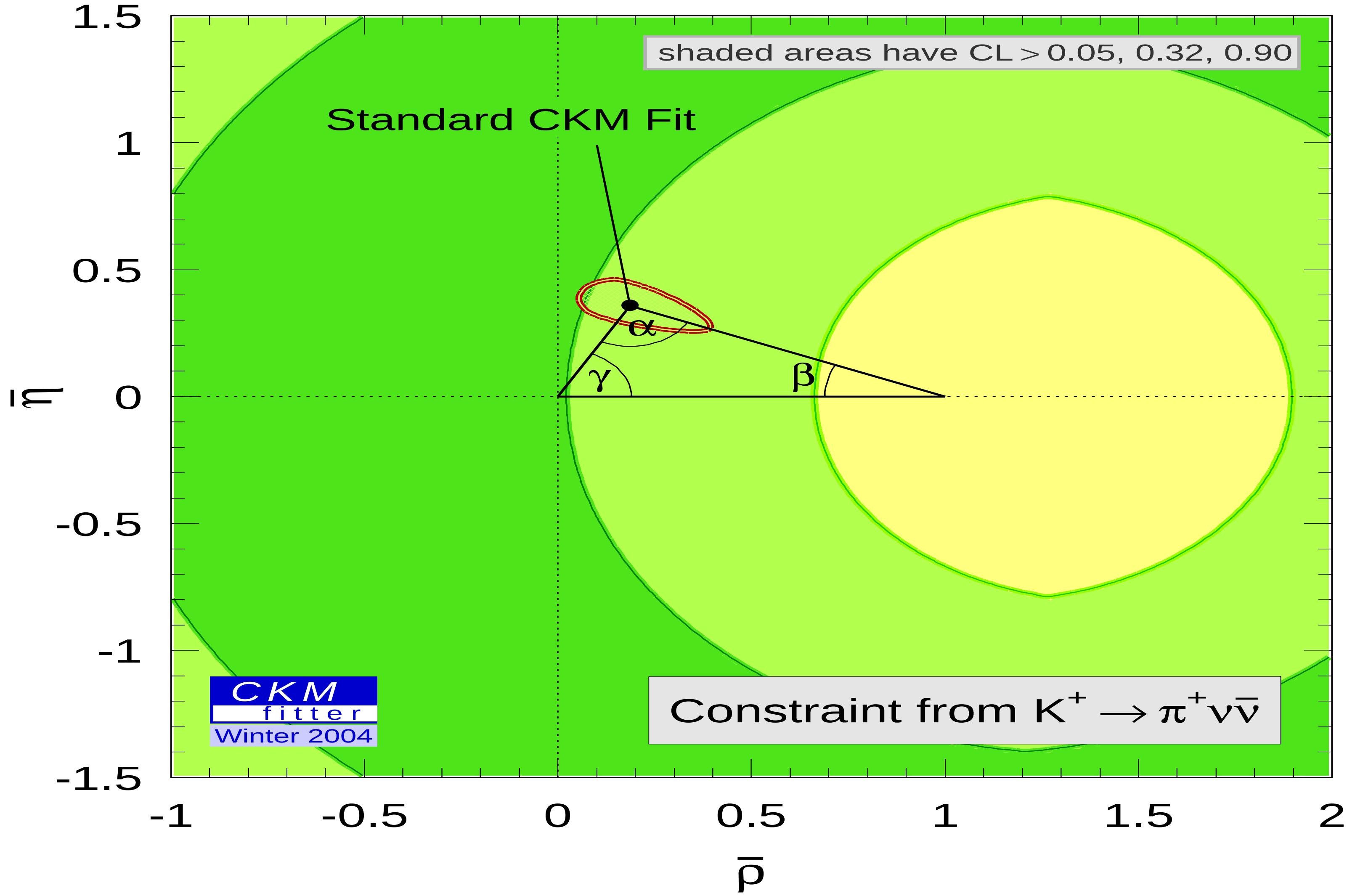
$\mathcal{B}(\mathrm{K_L} \to \pi^\circ \nu \overline{\nu}) < 1.4 \times 10^{-9}$ at 90% CL. [Grossman&Nir PL**B398**,163(1997)]

E787 result: $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \overline{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$

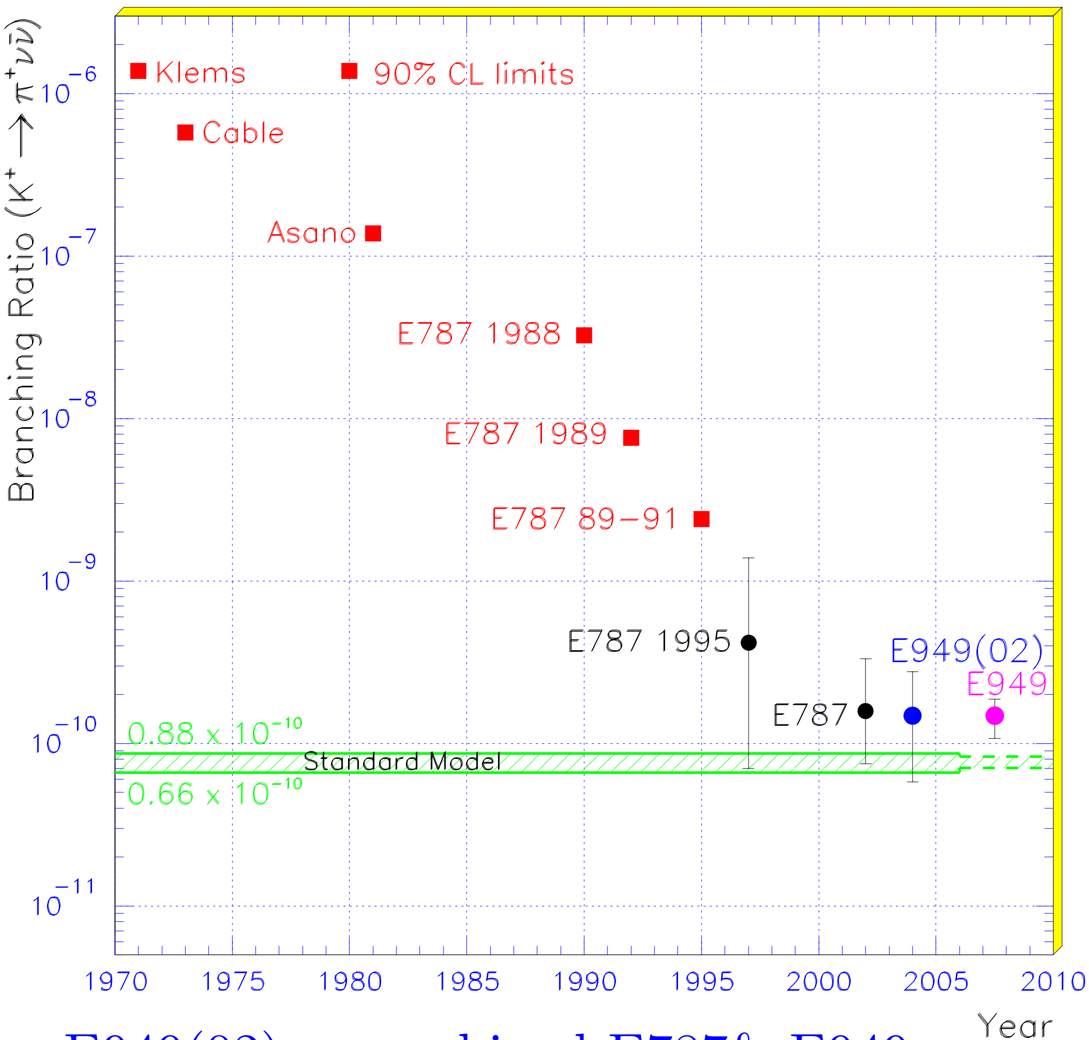
† Reference: Buchalla& Buras, NP**B548** 309 (1999);

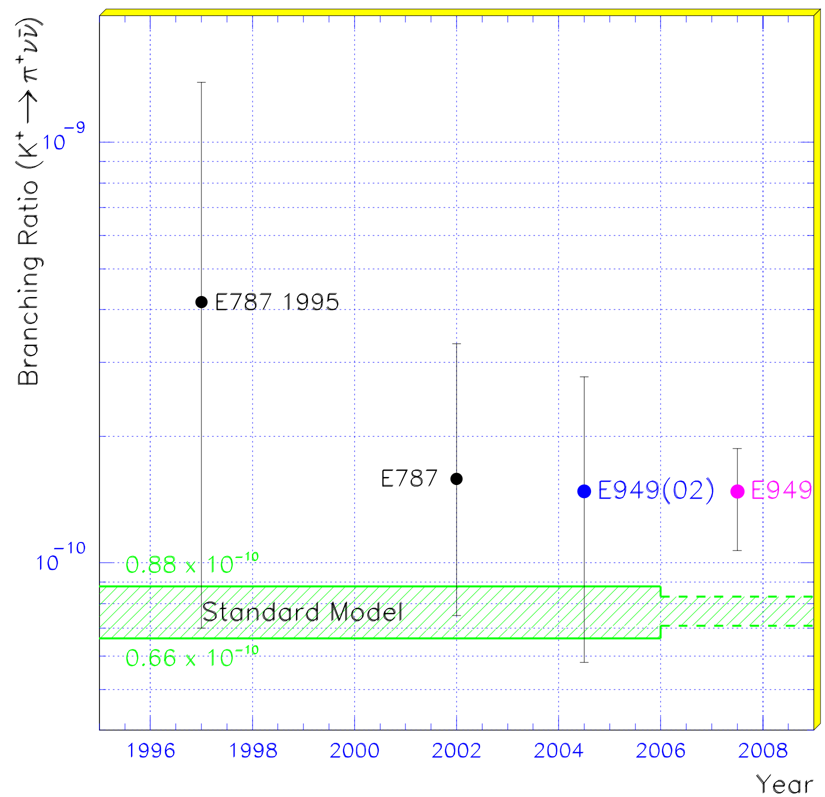
Isidori, hep-ph/0307014;Buras et al., hep-ph/0405132 ; Kettell, Landsberg & Nguyen, hep-ph/0212321

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ and the Unitarity Triangle



Progress in $K^+ \to \pi^+ \nu \bar{\nu}$





E949(02) = combined E787& E949.

E949 projection with full running period.

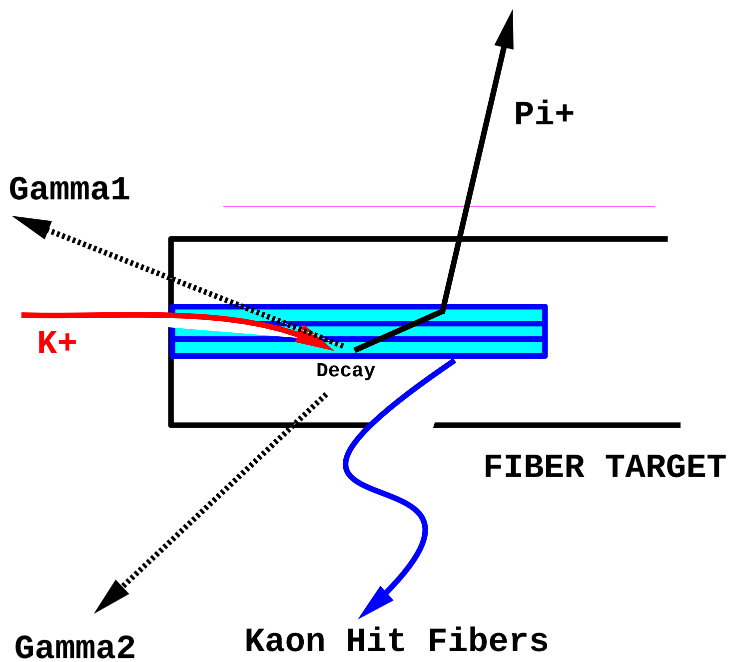
Narrowing of "SM prediction" assumes measurement of B_s mixing consistent with prediction.

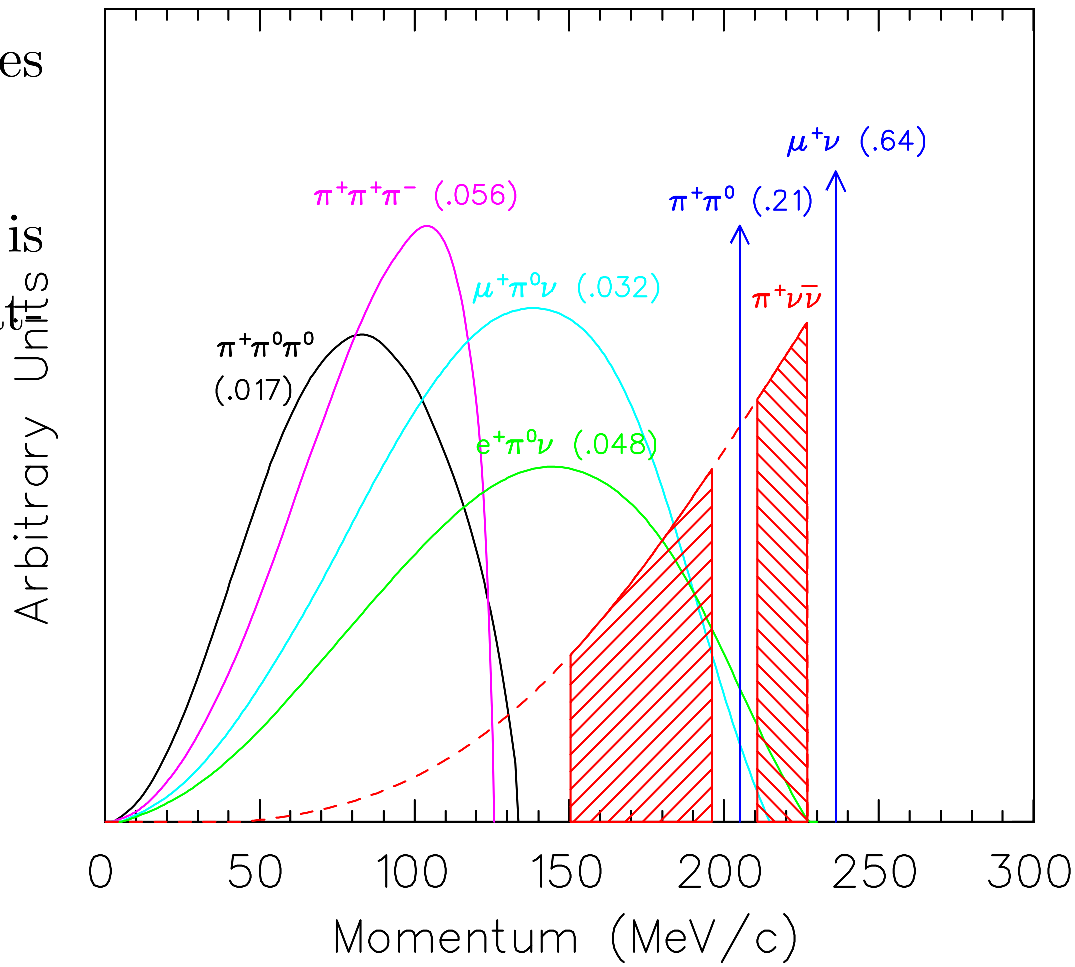
Very interesting .... so What Next?

- A 3^{rd} $K^+ \to \pi^+ \nu\overline{\nu}$ event has been observed. The BR remains 2×SM, but consistent with it.
  $\Longrightarrow$ **More data is needed.**
- E949 is analyzing more data (PNN2, phase space below the $K^+ \to \pi^+ \pi^\circ$ peak)
  - Two students working on theses on PNN2, one on $\pi^\circ \to \nu\overline{\nu}$, and one on $K^+ \to \pi^+ \gamma\gamma$.
- More E949 running?

PNN2: $K^+ \to \pi^+\nu\bar{\nu}$ below $K^+ \to \pi^+\pi^0$ peak

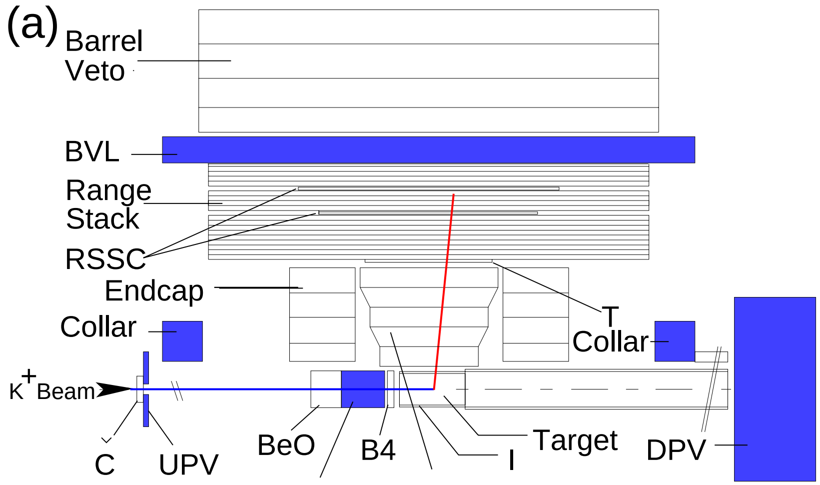
- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140{,}195)$ MeV/c probes more of $K^+ \to \pi^+\nu\bar{\nu}$ spectrum
- Main background mechanism is $K^+ \to \pi^+\pi^0$ followed by π^+ scatter in target.

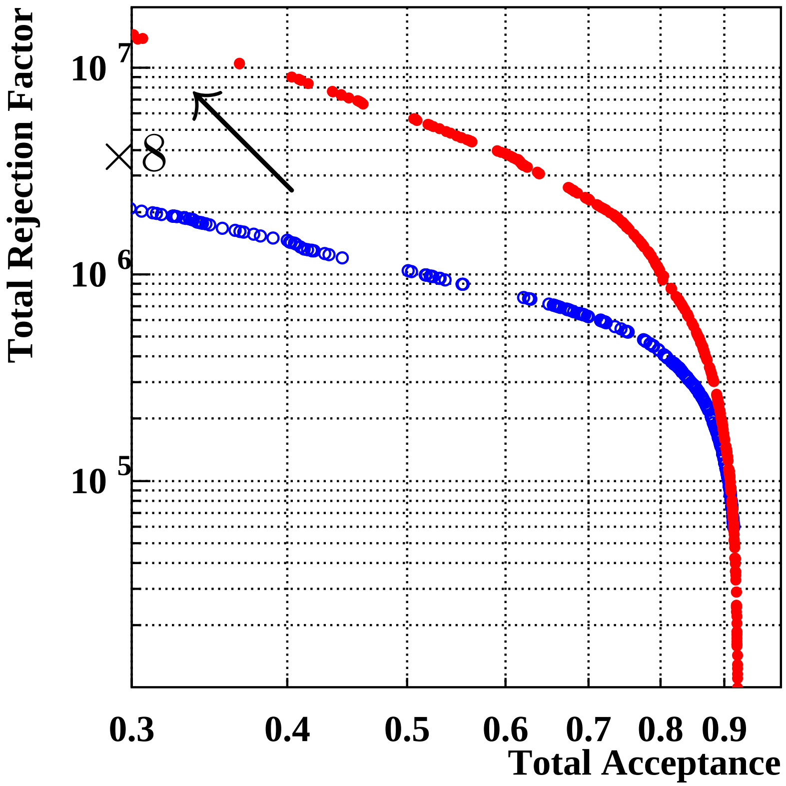




E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies $\times 2$ increase in acceptance and $\times 5$ increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \rightarrow \pi^+\pi^0$ followed by π^+ scatter in target.





What about more running of E949

• E949 was evaluated as 'must do' by the BNL PAC and approved by BNL.

• E949 was approved by DOE-HEP in August 1999 to run for 60 weeks, concurrent with RHIC operation, over three years (FY01–03).

• HEP operations at AGS halted after FY02 with 12 weeks of successfull running. Upgrades performed as predicted.

• A proposal to continue running E949 has been submitted to the National Science Foundation

Conclusions

- Upgrades of E787 to create E949 were successful.

- E949 has observed an additional $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ candidate and measures $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\overline{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$. Although consistent with the SM prediction, this result is two times larger than expected.

- The detector and collaboration are ready to complete the experiment.

- E949 analysis of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ for $P(\pi^+) < 195$ MeV/c is in progress.

Critical tests of the Standard Model:

- Overconstrain β from $B_d^\circ \to \psi K_S^\circ$ and $K_L^\circ \to \pi^\circ\nu\overline{\nu}$ / $K^+ \to \pi^+\nu\overline{\nu}$
- Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+\nu\overline{\nu}$